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Development of a Source PM10 Sampling Train Using Emission Gas Recycle (EGR)

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Development of a Source PM_{10} Sampling Train Using Emission Gas Recycle (EGR)

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16. ABSTRACT

Measurement of accurate particulate emission factors in ducted sources with particle size segregation involves a compromise between two conflicting requirements. In order to avoid anisokinetic sampling bias over a duct traverse, the flow rate of gas entering the sampling nozzle must vary with the local duct velocity. However, to maintain constant cuts in an inertial particle sizing device, the flow rate through the device must remain constant. Furthermore, if a specific size cut (such as ten micrometers) is specified, the flow rate of the sampler is fixed by the stack gas temperature and composition. A sampling train has been constructed which introduces an adjustable amount of clean, reheated, recycled stack gas between the sampling nozzle and the inertial sizing device. The recycle fraction is adjusted to maintain a constant flow rate through the sizing device while the nozzle flow is varied to maintain isokinetic sampling. The EGR train was tested at three coal-fired utility boilers using inertial samplers without recycle gas and EPA Method 17 trains for reference measurements. A mean total particulate mass measurement using the EGR train differed from the reference nonrecycle train values by +9.0, -9.1, and +1.4 percent, respectively at the three sites. Mean PM-10 values differed by -8.3, -6.9, and 11.4 percent, respectively.

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Introduction

Accurate measurement of size-specific (i.e, PM_{10}) particulate emissions from a ducted source involves a compromise between the two conflicting requirements of isokinetic sampling across the traverse plane and constant sampler flow rate. In addition, as with total particulate sampling, spatial and temporal variations of the sample stream may cause inaccurate or unrepresentative emissions measurements. EPA reference methods for particulate sampling deal with these problems by specifications on the sampling location (Method 1) and by spatial and temporal averaging using a traversing protocol which collects a weighted average of particulate emissions at an array of points spanning the sample plane (Methods 5 and 17). With any particulate sampling, the gas velocity entering the nozzle must ideally equal the local duct velocity. If an imbalance occurs, the particulate matter collected will be selectively enriched or depleted due to inertial separation at the nozzle entrance. This effect is size-dependent, becoming more pronounced as the particle diameter increases. For total particulate sampling, this bias is minimized by the specification of isokinetic sampling (with a 10% tolerance) at each point. By varying the sample flow rate so that the nozzle velocity is within 10% of the local duct velocity, this requirement is easily obtained for samples which are not size-specific.

However, the additional constraint of constant flow rate for inertial particle sizing devices (impactors and cyclones) directly conflicts with the current protocol for isokinetic particulate sampling. In order to obtain a sharp collection efficiency curve at a particular stage of a given sizing device, the flow rate, determined as a function of the sample gas temperature and composition, must remain constant. Without a sampling nozzle of continuously variable cross-sectional area, this fixed flow rate requirement makes isokinetic sampling in the manner outlined in Method 5 impossible. Historically, these samplers have been operated at fixed flow rates which produced nozzle velocities equal to the mean duct velocities as determined by EPA Reference Method 2. This choice avoids errors introduced by varying internal flow rates, but introduces errors caused by nonisokinetic sampling over the traverse. Since an isokinetic sampling bias can be significant for large particle diameters, including particles near 10 μm, this effect cannot be ignored in particle size sampling.

Several alternate sampling train designs have been considered which would allow isokinetic sampling over a full duct traverse while maintaining a constant flow rate through an inertial sizing device.[1,2,3] These include such concepts as variable area nozzles, split stream sampling probes, probe shroud extractive sampling, and gas recycle concepts. The gas recycle concept was subsequently developed into a prototype sampling train without an inertial sizing stage at EPA's Research Triangle Park facility where initial testing was conducted.[4] Under contract to Southern Research Institute, the emission gas recycle (EGR) concept was developed into a "field usable" system. This train first demonstrated the application of the EGR concept to particle size sampling.[5] Additionally, under this contract the EGR train was first used for field source sampling applications. The sampling train's design allows a preselected

constant flow rate through the inertial sampler while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. The prototype train was constructed by modifications of a commercially available EPA Reference Method 5 sampling system, and much of the sampling technique is identical with Method 5 protocol. In this paper we will briefly explain the EGR principle of operation, describe the sampling train, and present the results of field testing at three separate coal-fired utility boilers.

Principle of Operation

The principle of operation of the EGR train is illustrated in Figure 1. Stack gas is extracted isokinetically at volumetric flow rate Q_s. If the stack moisture fraction is B_{ws}, the sample flow consists of $Q_s \cdot B_{ws}$ moisture and $Q_s(1- B_{ws})$ dry gas flow. At the mixing point a flow, Q_r, of dry recycle gas is added to the sample stream to bring the total flow rate to the predetermined constant level, Q_t. In the impingers or condenser, the moisture content $B_{ws} \cdot Q_s$ is removed. After the pump and total flow metering element, the recycle flow Q_r is diverted by means of an adjustable valve. By mass balance, in a leak-free system the remaining flow which passes the dry gas meter and orifice will simply be $Q_s(1-B_{ws})$ exactly as would occur in an isokinetic sampling train without gas recycle.

There are several practical requirements for a functional EGR sampling system. The operator must be able to monitor and control accurately two flow rates rather than one. Setup and operation of the train must be simple, and the train must function reliably in normal field sampling environments. The recycle gas mixing must not cause significant particle deposition, must not perturb the cutpoints of the inertial sizing device, and must not introduce artifact particulate matter. In order to meet these constraints, the EGR train was constructed by modifications to the control module and sampling hardware of a commercially available Method 5 sampling train. Laminar flow elements are used to monitor the recycle and total flow rates. In order to minimize particulate losses, the recycle gas is introduced coaxially in an annulus around the sample gas.

A block diagram of the prototype field EGR train is shown in Figure 2. Stack gas is isokinetically extracted through the sample portion of the EGR mixing nozzle into Cyclone SoRI-I,[6] the initial sizing component of the sample train. After passing the inertial sizing device and instack sample filter, the sample gas passes through the probe and condenser or impinger train and into the EGR flow control module. As in conventional Method 5 control modules, the gas flowrate entering the control module is controlled by coarse and fine control valves (V_1 and V_2, respectively) at the entrance of the sealed pump. At the exit of the pump and absolute filter the total flow is measured using a laminar flow element (LFE). The gas stream is then split into the recycle and sample flow lines. The sample flow is monitored in the normal manner using a dry gas meter and a calibrated orifice. The recycle gas flowrate is measured using a second laminar flow element. The partitioning between sample and recycle gas is controlled by a valve (V_3) located downstream of the LFE. Valve V_4

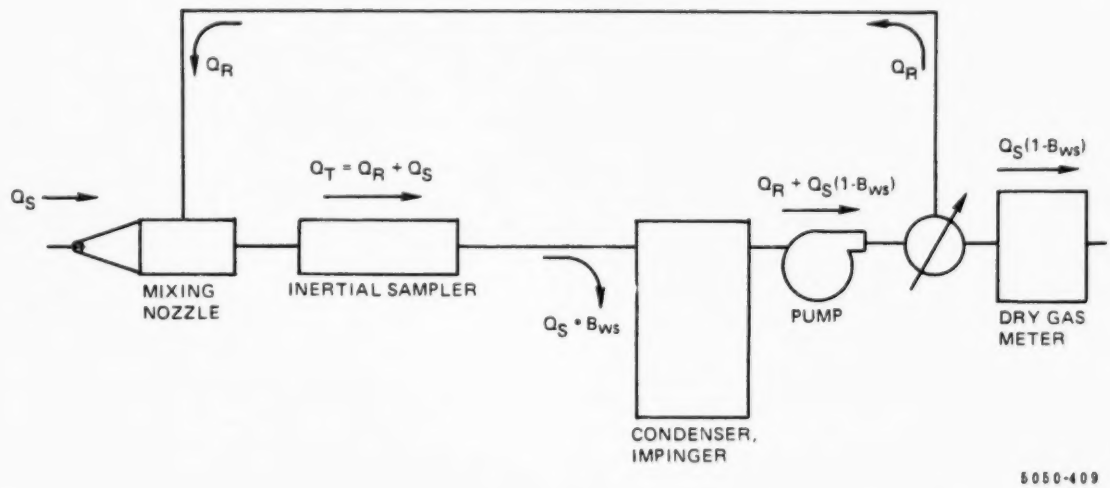

Figure 1. Gas flow in emission gas recycle (EGR) train.

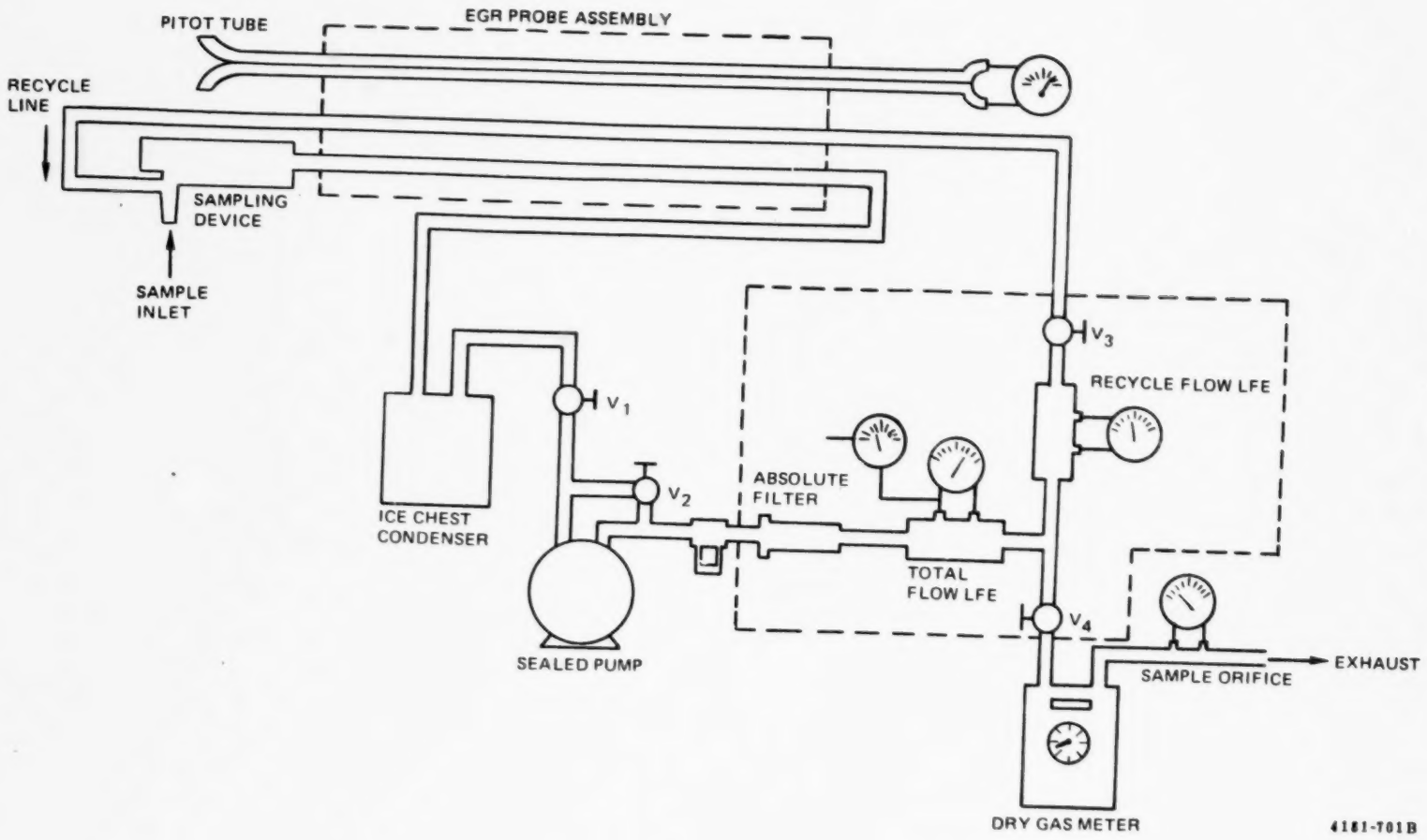

Figure 2. Schematic of the emission gas recycle train.

extends the range of control to higher recycle percentages by adding back pressure to the sample flow line. The recycle gas line, along with the sample and pitot lines, pass through the heated probe in which the recirculated gas is reheated to the duct temperature. Power to the heater is regulated by a proportional temperature controller using a thermocouple reference sensor located in the gas stream downstream of the heater.

Operation of the EGR train is similar to standard Method 5 sampling. The total dry gas flow $Q_r + Q_s(1-B_{ws})$ is monitored by using the total flow LFE and controlled using valves V_1 and V_2. The sampling flow Q_s (defined as the gas flowrate entering the nozzle) is monitored using the sample orifice and dry gas meter in the normal manner of Method 5 sampling, and controlled using the recycle valve V_3. Selection of traverse points and sample flowrate are done using standard techniques. In practice, the total flow would first be set to its operating value, then the sample flowrate adjusted to be isokinetic at the first traverse point. Changes in the recycle flow setting alter the total flow only slightly, so that one or two quick iterations of V_2 and V_3 are needed at a new traverse point. V_4 needs only to be adjusted once before a sample run to insure that the maximum necessary recycle flow can be attained. The only aspect that can be initially confusing to a trained Method 5 operator is that the sample flowrate is adjusted using the recycle valve rather than the customary valves V_1 and V_2.

The operation of the prototype system was verified in laboratory experiments comparing the EGR system with conventional isokinetic sampling systems in areas of total mass collection and particle size distribution. Wind tunnel comparisons, using redispersed fly ash, showed the EGR system collected an average of 1.2% less total mass, with a 95% confidence interval of ±4.1%, than a parallel sampling system without recycle. From the same data, the first stage of the EGR sampler indicated an average catch 7.0% (±5.8) less than the first stage of the conventional sampler.

Field Measurements Using the EGR System

The Emission Gas Recycle System was used to measure total mass and particulate size fractions at three separate coal-fired power plants. The test series compared results from the EGR system with those from standard Method 17 mass train systems, conventional cyclone and impactor trains, and similar trains using another PM_{10} candidate method (SIM5).[7] During the first two tests, the EGR and conventional cyclone train consisted of Cyclones I and IV of the SoRI/EPA series cyclone train, followed by a 47 mm glass fiber filter. For the final test of the series, a full SoRI five-stage series cyclone system was used for both systems. University of Washington Mark V impactors were also used for comparisons in all testing.

General Observations from Field Operation

During the course of the field testing program, many practical aspects of operation became apparent. First, several minor design flaws were discovered in the system. The heated probe as originally designed is heavier than desirable for easy traversing and transportation. Likewise, the packaging of the two EGR control boxes is somewhat unwieldy. The method of mounting the pitot head made it tedious to set and maintain the pitot alignment with respect of the nozzle. With the initial design it was possible to inadvertently reverse the sample and recycle lines to the EGR control box. This actually occurred on the second test, causing one run to be invalidated. After this test, the umbilical was changed to prevent line reversal in future operations.

The EGR system is of necessity somewhat more difficult to operate than Method 5 or conventional inertial sizing trains. One problem with the current EGR/Cyclone I system is the slightly greater length of the EGR nozzle. The added nozzle length, combined with the extra hardware (pitot head, recycle lines) on the probe head and the extra weight of the probe body made port entry and exit more difficult. Some care must be exercised to avoid scraping the nozzle on the port walls. Leak checks are also somewhat more complicated in that separate checks of the recycle lines within the control box are advisable. Sampling with the EGR system is somewhat more complex since the operator must monitor two or three additional pressure drops and perform one additional flowrate adjustment at each traverse point. The burden on the operator is not excessive, however, and new operators typically "get the feel" of the system after a few adjustments of the flowrates. The most complex aspect of sampling seems to be the setup calculations, in which the target pressure drops for the sample orifice and the total flow LFE are obtained for different stack gas temperatures and velocities (as measured by the pitot ΔP). Once adjusted, the flowrates appear to be as stable as is typical for Method 5 or cascade impactor sampling.

Test No. 1

The first field test took place at one of the twin 56 MW coal-fired boilers at a utility generating station. The plant nominally operates at minimum (half) load; however, boiler conditions occasionally changed as dictated by demand. The sampling location chosen was the ducting between an outdated, somewhat inefficient electrostatic precipitator and a retrofitted, more efficient ESP.

The test plan was divided into two subtests. Subtest A involved the comparison of traverses performed with the EGR train and a standard Method 17 (M17) mass train. To eliminate spatial bias, a probe was configured with a cylcone set[6] (SoRI Cyclone I, Cyclone IV and a 47 mm filter) using an EGR nozzle and a collocated 47 mm filter. The large diameter of this system required plant installation of six-inch ports. Three traverse points were selected which represented the maximum point-to-point velocity change accessible through the six-inch ports. The recycle rate was then adjusted to achieve isokinetic sampling at each point while maintaining

the chosen constant flow rate through the cyclone set. The flow rate through the collocated 47 mm filter was adjusted at each point according to isokinetic sampling protocol.

In Subtest B, the EGR-M17 hardware described under Subtest A was used without modification. A second cyclone train, without emission gas recirculation, was used for a "near-collocated" reference. This train used identical cyclone samplers equipped with a standard nozzle rather than the EGR nozzle. The remainder of the sampling train was conventional: a heated stainless steel probe, ice bath condenser, and a commercial Method 5 control box. Both probes (three sampling trains) were inserted at right angles to each other in order to sample the same duct point (within approximately four-inch nozzle-to-nozzle spacing). The duct point and nozzle for the nonrecycle were selected so that the isokinetic flowrate was slightly greater than the flow rate calculated for a 10 μm D_{50} in the cyclone. The isokinetic flow rate rather than the PM_{10} flow rate was used for sampling. The EGR cyclone was fitted with a smaller nozzle than the nonrecycle train. The EGR sample flow rate was adjusted to maintain isokinetic nozzle sampling. The recycle fraction was adjusted to make the cyclone flow rate identical to that used for the nonrecycle cyclone. The Method 17 sampler was again adjusted in the usual fashion.

A total of eight valid EGR comparison tests were performed during the initial field test. Sampling runs 2 through 6 were completed as described under Subtest A. With the exception of Run 3, which was performed during a boiler fluctuation, these were performed with the boiler at full load (56 MW). Runs 7 through 10 were replicates for Subtest B, all of which were run at minimum boiler conditions (28 MW).

The run parameters, along with the total mass and nominal-PM_{10} loadings are shown in Table I. The recycle rates (shown as percentage of the total cyclone flow rate) varied from 9.6% to 59.6% throughout the duration of the testing.

Test No. 2

The second EGR field test was carried out at a 500 MW coal-fired power plant. The plant consisted of two 250 MW units with each unit controlled by two cold-side electrostatic precipitators. The sampling location chosen was between the outlet of one ESP and the stack. Pretest surveys indicated the duct velocity averaged 60 ft/sec, with substantial velocity spread. An aerosol mass median diameter in the 7-14 μm diameter range was expected. As previously mentioned, the cyclone trains used for the second field test were identical to those used for the first test (SoRI Cyclone I, Cyclone IV, and a 47 mm quartz-fiber backup filter). The EGR cyclone train simultaneously sampled a three-point traverse along with a standard sampling cyclone train following another candidate PM_{10} sampling protocol referred to as SIM5 (Synthetic Method 5).[7]

The flow rates through both trains were set to produce a 10 μm aerodynamic D_{50} through the first cyclone. The nonrecycle (SIM5) cyclone train sampled across the traverse with isokinetic ratio varying from

Table I. EGR test 1 run parameters.

	Sample Flow (acfm)	Percent Recycle	Percent Isokinetic	Boiler Load (MW)	Mass Loading (mg/dnm^3)	PM_{10} Loading (mg/dnm^3)
Run 2						
M17	0.67	--	164.3	56	1557[a]	--
EGR	0.56	18.0	98.1		2053	453
Run 3						
M17	0.57	--	99.4	34	586	--
EGR	0.33	59.6	96.8		543	113
Run 4						
M17	0.40	--	96.1	55	2397	--
EGR	0.59	15.6	100.9		1952	391
Run 5						
M17	0.42	--	100.6	56	2077	--
EGR	0.62	15.7	107.5		1804	411
Run 6						
M17	0.48	--	107.7	56	1888	--
EGR	0.64	9.6	104.5		1808	399
Run 7						
M17	0.49	--	104.7		61.9	--
EGR	0.57	20.8	105.9	28	42.9	17.8
STD	0.66	--	89.7		46.5	18.5
Run 8						
M17	0.45	--	107.2		87.9	--
EGR	0.53	41.6	108.8	28	75.7	21.8
STD	0.67	--	102.7		57.2	21.8
Run 9						
M17	0.49	--	111.9		65.3	--
EGR	0.55	33.6	111.0	28	63.9	20.5
STD	0.74	--	107.9		67.0	28.8
Run 10						
M17	0.47	--	99.7		80.9	--
EGR	0.56	34.9	101.9	28	74.5	27.8
STD	0.74	--	100.6		60.4	26.6

[a] M17 control box malfunction--run deleted from test averages.

83% to 145% as outlined in the SIM5 protocol.[7] By using a slightly smaller nozzle on the EGR system, the nozzle sampled isokinetically while the total cyclone flow rate was keep constant with the addition of variable amounts of recycle gas. Eight replicates of the paired measurements were initiated. However, equipment malfunction invalidated the first two EGR runs, and the fifth EGR/SIM5 run was aborted after the boiler dropped from 240 MW to 90 MW due to plugging of a fuel feed line. The run parameters, total mass loadings, and PM_{10} mass loading for these tests are shown in Table II. As with the first field test, the samples were obtained within 10% of the isokinetic ratio. In this test series the recycle rates experienced were consistently around 46%.

Test No. 3

The site chosen for the third EGR field test was a 221 MW coal-fired utility boiler. Sampling took place at the inlets to two identical particulate control devices. Eight four-inch ports provided access to the duct interior on each unit. The velocity of Duct A ranged from 37 to 64 ft/sec, with a mean velocity of approximately 51 ft/sec. Duct B had a velocity range of 45 to 61 ft/sec, with an average of 53 ft/sec.

The test plan called for a concurrent EGR/nonrecycle (SIM5) test series similar to that of Test No. 2. The flow rate for each train was chosen such that the aerodynamic D_{50} for the first cyclone was 10 μm. Across the traverse, the EGR nozzle sampled isokinetically while a constant cyclone flow rate was maintained using a variable fraction of recycle gas. The nonrecycle cyclone train once again sampled according to SIM5 protocol. In this test, full duct (12-point) PM_{10} measurements were performed rather than the three-point sample in Test 2. Each 12-point traverse involved sampling at three points in four of the eight ports. The eight ports available for sampling on each duct were grouped into two sets of four, ACEG and BDFH. Four sets of simultaneous EGR and nonrecycle (SIM5) runs were performed at the inlet to Unit A. Two traverses were performed in ports ACEG and two in ports BDFH. Two replicates were performed in Duct B using ports ACEG. The sampling hardware used for both the EGR and nonrecycle (SIM5) trains throughout this testing consisted of full SoRI Five-Stage Series Cyclone sets. The run parameters and loadings for the paired cyclone runs are shown in Table III. The recycle rate averaged about 48% with little variation.

Results and Conclusions

Average particulate concentrations and 95% confidence limits from the run data measured in the test series are summarized in Table IV. As can be seen, the tests cover a broad range of particulate concentrations. At every site, the EGR train and the comparison device measured particulate concentrations which agreed within the combined confidence limits of the measurements. Table IV also presents the relative standard deviation (standard deviation expressed as a percentage of the mean value) of each set of runs. In two cases the relative standard deviation of the EGR is over 15% (Site 1 at low load and Site 2). At Site 2 the same degree of variation is seen in measurements with comparison devices. Since the testing coincided with a period of coal pulverizer problems, the

Table II. EGR test 2 run parameters.

	Sample Flow (acfm)	Percent Recycle	Percent Isokinetic	Mass Loading (mg/dnm^3)	PM_{10} Loading (mg/dnm^3)
Run 1					
EGR	0.40	38.9	111.7	--[a]	110
SIM5	0.60	--	95.1	264	124
Run 2					
EGR	0.33	47.7	98.4	--[b]	--[b]
SIM5	0.61	--	94.0	213	109
Run 3					
EGR	0.34	46.5	96.5	195	94
SIM5	0.62	--	97.3	201	107
Run 4					
EGR	0.35	46.3	99.7	279	130
SIM5	0.59	--	92.4	307	138
Run 6					
EGR	0.34	48.6	99.1	115	56
SIM5	0.61	--	100.2	130	66
Run 7					
EGR	0.34	47.5	99.6	200	86
SIM5	0.60	--	94.4	207	104
Run 8					
EGR	0.36	45.3	97.1	189	79
SIM5	0.60	--	91.7	228	104

[a]Excessive nozzle scrape -- total mass not included in test averages.
[b]Invalidated run -- deleted from test averages.

Table III. EGR test 3 run parameters.

	Sample Flow (acfm)	Percent Recycle	Percent Isokinetic	Sampling Duct	Mass Loading (mg/dnm^3)	PM_{10} Loading (mg/dnm^3)
Run 1						
EGR	0.30	48.4	101.3	A	3630	744
SIM5	0.60	--	97.2	A	4090	776
Run 2						
EGR	0.31	47.9	100.8	A	3570	791
SIM5	0.58	--	99.4	A	2920	659
Run 3						
EGR	0.32	44.0	98.9	A	2740	749
SIM5	0.51	--	105.1	A	3750	650
Run 4						
EGR	0.30	48.4	101.6	A	3810	752
SIM5	0.57	--	98.5	A	3830	660
Run 5						
EGR	0.31	49.1	99.4	B	3830	814
SIM5	0.56	--	120.8	B	3270	756
Run 6						
EGR	0.31	52.2	101.1	B	4330	969
SIM5	0.57	--	105.9	B	3680	794

Table IV. Average particulate concentrations observed in EGR test series.

	No. of Runs	Total Mass: Average Loading (mg/dnm^3)	Total Mass: Relative Standard Deviation (%)	PM_{10}: Average Loading (mg/dnm^3)	PM_{10}: Relative Standard Deviation (%)
Site 1					
High boiler load					
M17 mass train	3	2120 (±638)[a]	12.1	--	--
EGR cyclone train	4	1904 (±192)	6.3	413 (±44)	6.7
Low boiler load					
M17 mass train	4	74 (±20)	16.8	--	--
EGR cyclone train	4	65 (±24)	23.4	22 (±6.7)	19.1
Std. cyclone train	4	57 (±12)	13.2	23 (±7.5)	19.7
Site 2					
EGR cyclone train	6	196 (±72)	29.7	92 (±26)	7.1
SIM5 cyclone train	7	221 (±51)	24.9	107 (±23)	6.4
Site 3					
EGR cyclone train	6	3650 (±546)	14.3	803 (±90)	10.7
SIM5 cyclone train	6	3590 (±444)	11.8	716 (±70)	9.3

[a]95% confidence intervals are indicated for each mean particulate loading.

variability is easily attributable to source instability. Some indication of source variability was also noted at Site 1 at low load, although the variance of the EGR data is greater than that seen by the other techniques. It is also interesting to note that the precision of the PM_{10} measurements is better in every case than that of total mass measurements with the same device.

The test plan for all three sites included simultaneous measurements (collocated where possible) with the EGR train and suitable comparison devices in order to minimize the effects of source temporal variability. Table V contains a paired run analysis of the test data. The entries in Table V represent means and 95 percent confidence limits of individual run percentage differences for the paired measurements of total particulate mass or PM_{10} concentration. The percentage differences between the EGR and SIM5 values are relative to the mean of the two concentrations. No consistent trend is seen between the EGR and comparison measurements, and the differences typically do not exceed the 95% significance level.

In summary, the EGR train continues to be a promising technique for source particulate measurements. Future plans for the technique include correction of the few design deficiencies discovered during this test series, adaptation of the EGR concept to a cascade impactor for more detailed size distribution measurements, and further field validation of the device. We anticipate that the device has excellent potential to satisfy the requirements of a PM_{10} reference method.

Table V. Percentage difference between EGR cyclone train and reference device in paired runs.

	Number of Runs	Total Mass	PM_{10}
Site 1 (Method 17)	8	-11.5±8.3	--
Site 1 (Nonrecycle cyclone)	4	9.0±28.7	-8.3±27.4
Site 2 (SIM5 cyclone)	5	-9.3±8.4	-15±6.5
Site 3 (SIM5 cyclone)	6	1.6±20.0	11.4±9.7

[a]Quoted values represent the mean and 95 percent confidence limits of the difference between the EGR concentration and the comparison device concentration on individual runs, expressed as a percentage of the overall mean reference concentration.

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